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A photonic solution to exoplanet direct imaging via nulling interferometry

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Direct imaging of exoplanets is vital for understanding star system formation and the evolutionary behaviour of exoplanets at large orbits. Typically, imaging a star system to find an exoplanet requires significant attenuation of the host star's high flux in order to detect the much weaker planetary light. The most common method to do this is coronagraphy, which blocks the starlight with an amplitude mask or a null inducing phase mask [1]. An alternative and attractive method is nulling interferometry where light from multiple telescopes are used to simultaneously form a high resolution image (or its Fourier components) and also to form a null in the vicinity of the host star, thereby attenuating it [2]. This has the advantage over coronagraphy that it is not limited to using a single telescope and is thus able to probe deeper into a star system by virtue of the higher resolution available by an interferometric array.

Photonics is becoming commonplace in astronomy for several reasons: it is more robust to environmental effects as compared to bulk optics and fibre, it can reduce large optical tables down to centimetre scale chips, and it is alignment free once light is on the chip enabling far more complex processing than is viable with bulk optics. Due to photonics, future space missions will become more affordable by reducing the total weight and complexity of the system.

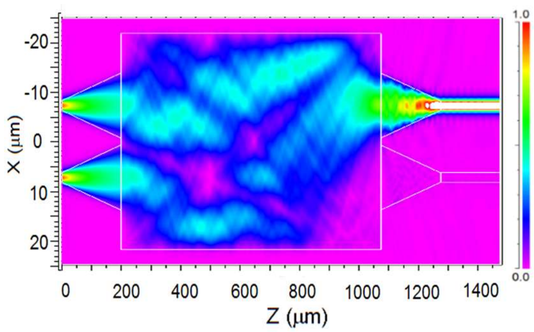

Figure 1: The basic design of a two telescope beam combiner using a multimode interference coupler. Light travels from left to right.

A basic photonic chip is shown in Fig. 1. It shows a 1 mm long multimode interference coupler (MMI) used as a two telescope nulling interferometer. Chalcogenide glass was used to make these photonic chips because it is transparent in the mid-infrared (MIR) [3]. Working in the MIR allows astronomers to take advantage of the improved contrast occurring in this region between exoplanets and typical stars [4]. Star systems with dimmer stars, like M dwarfs, provide a better contrast between exoplanets and the host star, but the trade-off is that the habitable zone of these stars requires a significantly higher angular resolution to image.

Working in the MIR is also beneficial for ground based instruments due to an atmospheric transmission window around 4 microns where the OH and CO_2 absorptions are greatly reduced. The longer wavelength reduces the impacts of atmospheric turbulence and "air glow" allowing for better imaging. This will aid the adaptive optics used when taking exoplanet images and potentially allow for greater exposure times.

The 4 μm band, however, is but a stepping stone in the field of exoplanet detection. For detection of O_3 on exoplanets, considered a key indicator of life [5], wavelengths around the 10 μm range are necessary but this comes with its own challengers. The Earth's atmosphere is bright at this wavelength due to its own blackbody radiation and the photonic technology and telescope design to make an interferometric detection at this wavelength is still in its infancy. A solution to this is to move to a space based interferometer that will orbit above the atmosphere and be cooled to around 40 K.

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The latest work at the ANU is the design and experimental verification of a two telescope nulling interferometer, fabricated on a chalcogenide photonic chip. The basic design is shown in Fig. 1. An MMI was chosen over other photonic combiners (like directional couplers and Y-junctions) as the beam combiner because of its known robust fabrication tolerance in respect to its transmission [6]. In previous work it was been shown that the MMI's robust fabrication tolerance also extends to its imbalance – the ability to split light evenly and thus to form a deep null [7]. Note that this is however limited to a single wavelength but at a cost of 20% transmission the low imbalance region can be extended to 400 nm [8]. This is shown in Fig. 2.

Figure 2 is the experimental verification of what has previously been simulated – a wide band MMI. This shows that a single MMI can be designed to split light evenly over a 400 nm bandwidth.

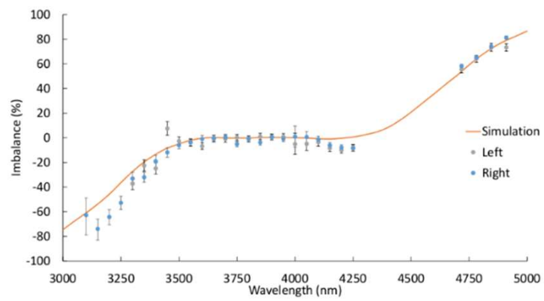

Figure 2: Imbalance measurement of the left (grey) and right (blue) input port, in respect to the beam direction of Fig. 1, compared to a simulation (yellow) of an MMI that had same dimensions (width, length and taper width) as the real version.

The implication of Fig. 2 is that when used as a beam combiner a deep null will form over this bandwidth. The depth of this null is yet to be determined experimentally but from simulations a 40 dB null depth over the entire bandwidth should be possible.

The final goal for this project is to design a multi-beam combiner that brings starlight to a null and allows for a clear image of the orbiting exoplanets. A Kernel-Nulling interferometer is one proposed method of achieving this. To begin working on this interferometer the current technology must be adapted to accommodate the beam from four telescopes at the Very Large Telescope Interferometer. This is a part of a larger mission known as VIKiNG [9]. One version of this is a cascade of MMIs used to null the starlight, with the null ports directed to a sensing cavity. This the kernel phase to improve the image quality and resolution.

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